11 TRANSFORMER PROTECTION

This chapter describes the protection practices for transformers of the following types whose three-phase bank rating is 501 kva and higher:

Power transformers

Power autotransformers

Regulating transformers

Step voltage regulators

Grounding transformers

Electric arc-furnace transformers

Power-rectifier transformers

Contrasted with generators, in which many abnormal circumstances may arise, transformers may suffer only from winding short circuits, open circuits, or overheating. In practice relay protection is not provided against open circuits because they are not harmful in themselves. Nor in general practice, even for unattended transformers, is overheating or overload protection provided; there may be thermal accessories to sound an alarm or to control banks of fans, but, with only a few exceptions, automatic tripping of the transformer breakers is not generally practiced. An exception is when the transformer supplies a definite predictable load. External-fault back-up protection may be considered by some a form of overload protection, but the pickup of such relaying equipment is usually too high to provide effective transformer protection except for prolonged short circuits. There remains, then, only the protection against short circuits in the transformers or their connections, and external-fault back-up protection. Moreover, the practices are the same whether the transformers are attended or not.

POWER TRANSFORMERS AND POWER AUTOTRANSFORMERS

THE CHOICE OF PERCENTAGE-DIFFERENTIAL RELAYING FOR SHORT-CIRCUIT PROTECTION

It is the practice of manufacturers to recommend percentage-differential relaying for short-circuit protection of all power-transformer banks whose three-phase rating is 1000 kva and higher.[1] A survey of a large number of representative power companies showed that a minority favored differential relaying for as low as 1000-kva banks, but that they were

practically unanimous in approving differential relaying for banks rated 5000 kva and higher.[2] To apply these recommendations to power autotransformers, the foregoing ratings should be taken as the "equivalent physical size" of autotransformer banks, where the equivalent physical size equals the rated capacity times $[1 - (V_L/V_H)]$, and where V_L and V_H are the voltage ratings on the low-voltage and high-voltage sides, respectively.

The report of an earlier survey[3] included a recommendation that circuit breakers be installed in the connections to all windings when banks larger than 5000 kva are connected in parallel. The more recent report is not very clear on this subject, but nothing has transpired that would change the earlier recommendation. The protection of parallel banks without separate breakers and the protection of a single bank in which a transmission line terminates without a high-voltage breaker will be considered later.

The differential relay should operate a hand-reset auxiliary that will trip all transformer breakers. The hand-reset feature is to minimize the likelihood of a transformer breaker being reclosed inadvertently, thereby subjecting the transformer to further damage unnecessarily.

Where transmission lines with high-speed distance relaying terminate on the same bus as a transformer bank, the bank should have high speed relaying. Not only is this required for the same reason that the lines require it, but also it permits the second-zone time of the distance relays "looking" toward the bus to be set lower and still be selective.

CURRENT-TRANSFORMER CONNECTIONS FOR DIFFERENTIAL RELAYS

A simple rule of thumb is that the CT's on any wye winding of a power transformer should be connected in delta, and the CT's on any delta winding should be connected in wye. This rule may be broken, but it rarely is; for the moment let us assume that it is inviolate. Later, we shall learn the basis for this rule. The remaining problem is how to make the required interconnection between the CT's and the differential relay.

Two basic requirements that the differential-relay connections must satisfy are: (1) the differential relay must not operate for load or external faults; and (2) the relay must operate for severe enough internal faults.

If one does not know what the proper connections are, the procedure is first to make the connections that will satisfy the requirement of not tripping for external faults. Then, one can test the connections for their ability to provide tripping for internal faults.

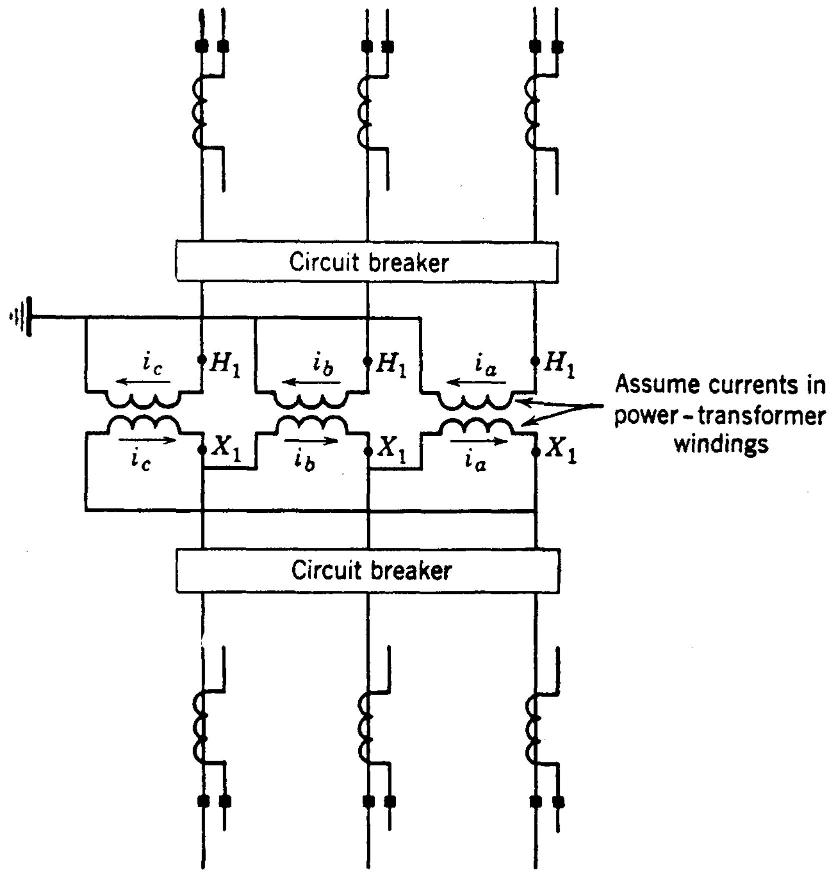


Fig. 1. Development of CT connections for transformer differential relaying, first step.

As an example, let us take the wye-delta power transformer of Fig. 1. The first step is arbitrarily to assume currents flowing in the power-transformer windings in whichever directions one wishes, but to observe the requirements imposed by the polarity marks that the currents flow in opposite directions in the windings on the same core, as shown in Fig. 1. We shall also assume that all the windings have the same number of turns so that the current magnitudes are equal, neglecting the very small exciting-current component. (Once the proper connections have been determined, the actual turn ratios can very easily be taken into account.)

On the basis of the foregoing, Fig. 2 shows the currents that flow in the power-transformer leads and the CT primaries for the general external-fault case for which the relay must not trip. We are assuming that no current flows into the ground from the neutral of the wye winding; in other words, we are assuming that the three-phase currents add vectorially to zero.

The next step is to connect one of the sets of CT's in delta or in wye, according to the rule of thumb already discussed; it does not matter how the connection is made, i.e., whether one way or reversed.

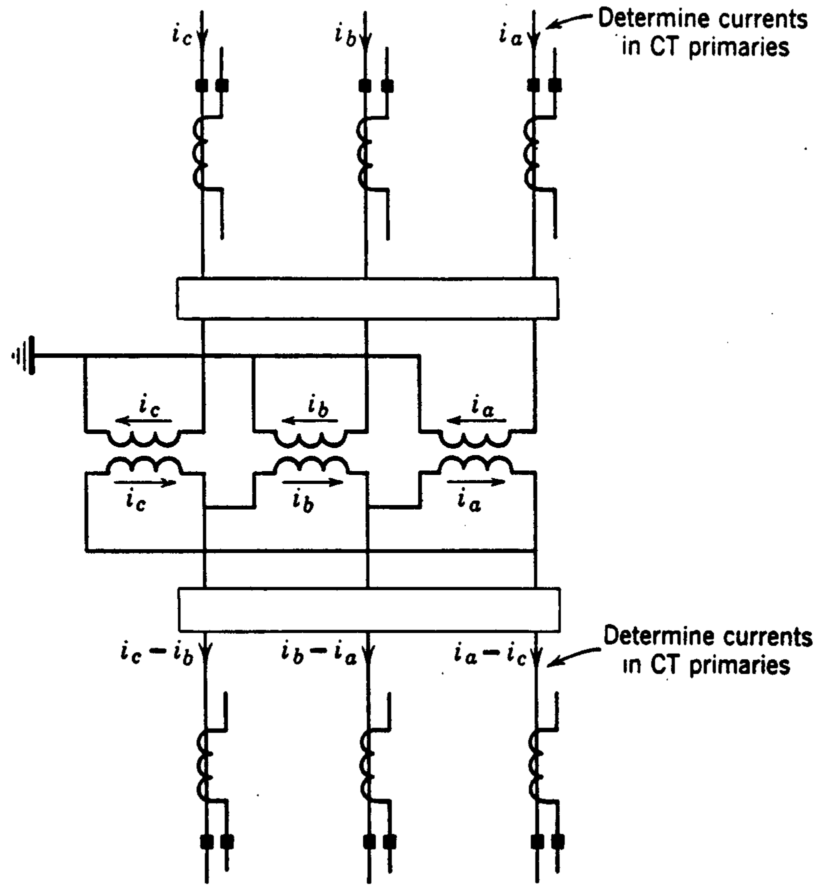


Fig. 2. Development of CT connections for transformer differential relaying, second step.

Then, the other set of CT's must be connected also according to the rule, but, since the connections of the first set of CT's have been chosen, it does matter how the second set is connected; this connection must be made so that the secondary currents will circulate between the CT's as required for the external-fault case. A completed connection diagram that meets the requirements is shown in Fig. 3. The connections would still be correct if the connections of both sets of CT's were reversed.

Proof that the relay will tend to operate for internal faults will not be given here, but the reader can easily satisfy himself by drawing current-flow diagrams for assumed faults. It will be found that protection is provided for turn-to-turn faults as well as for faults between phases or to ground if the fault current is high enough.

We shall now examine the rule of thumb that tells us whether to connect the CT's in wye or in delta. Actually, for the assumption made in arriving at Fig. 2, namely, that the three-phase currents add vectorially to zero, we could have used wye-connected CT's on the wye side and delta-connected CT's on the delta side. In other words, for all external-fault conditions except ground faults on the wye side of the bank, it would not matter which pair of CT combinations was used. Or, if the neutral of the power transformer was not grounded, it would not matter. The significant point is that, when ground current can flow

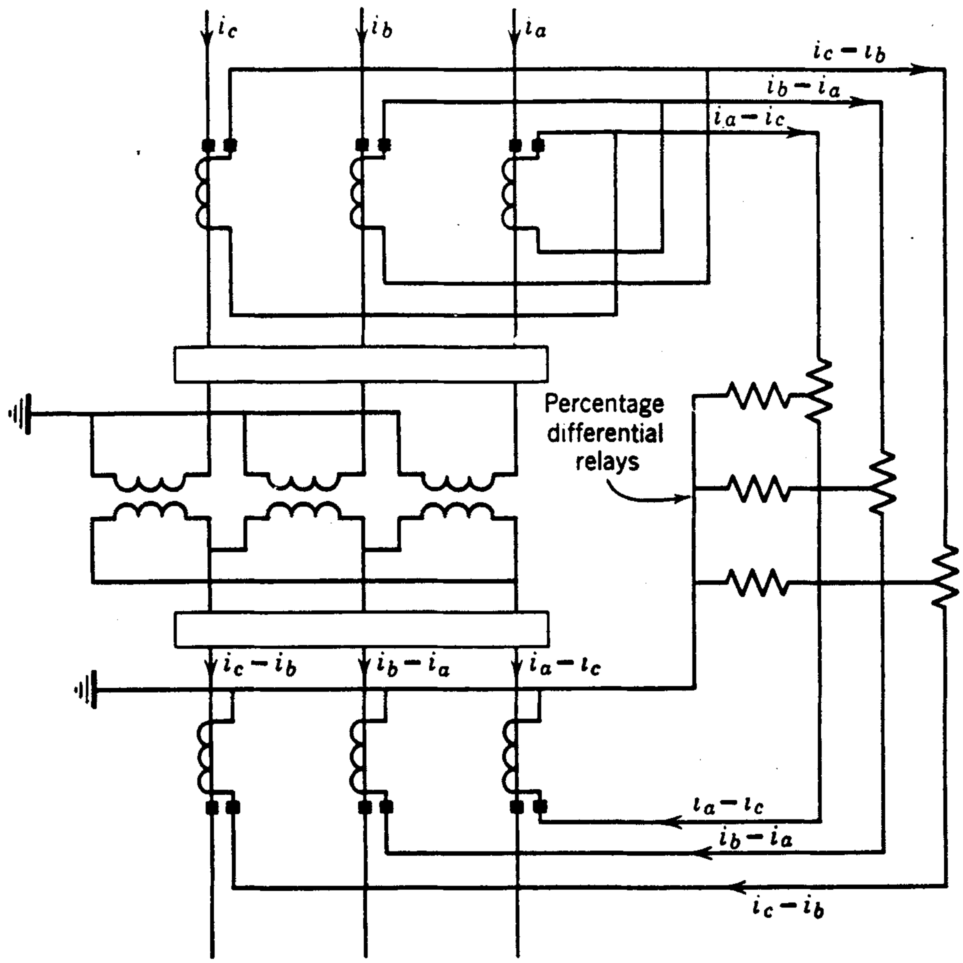


Fig. 3. Completed connections for percentage-differential relaying for two-winding transformer.

in the wye windings for an external fault, we must use the delta connection (or resort to a "zero-phase-sequence-current-shunt" that will be discussed later). The delta CT connection circulates the zero-phase-sequence components of the currents inside the delta and thereby keeps them out of the external connections to the relay. This is necessary because there are no zero-phase-sequence components of current on the delta side of the power transformer for a ground fault on the wye side; therefore, there is no possibility of the zero-phase-sequence currents simply circulating between the sets of CT's and, if the CT's on the wye side were not delta connected, the zero-phase-sequence components would flow in the operating coils and cause the relay to operate undesirably for external ground faults.

Incidentally, the fact that the delta CT connection keeps zero-phase-sequence currents out of the external secondary circuit does not mean that the differential relay cannot operate for single-phase-to-ground faults in the power transformer; the relay will not receive zero-phase-sequence components, but it will receive–and operate on–the positive- and negative-phase-sequence components of the fault current.

The foregoing instructions for making the CT and relay interconnections apply equally well for power transformers with more than two windings per phase; it is only necessary to consider two windings at a time as though they were the only windings. For example, for three-winding transformers consider first the windings *H* and *X*. Then, consider *H* and *Y*, using the CT connections already chosen for the *H* winding, and determine the connections of the *Y* CT's. If this is done properly, the connections for the *X* and *Y* windings will automatically be compatible.

Figure 4 shows schematic connections for protecting the main power transformer and the station-service power transformer where a generator and its power transformer operate as a unit. To simplify the picture, only a one-line diagram is shown with the CT and power-transformer connections merely indicated. It will be noted that one restraint coil is supplied by current from the station-service-bus side of the breaker on the low-voltage side of the station-service power transformer in parallel with the CT in the neutral end of the generator winding; this is to obtain the advantage of overlapping adjacent protective zones

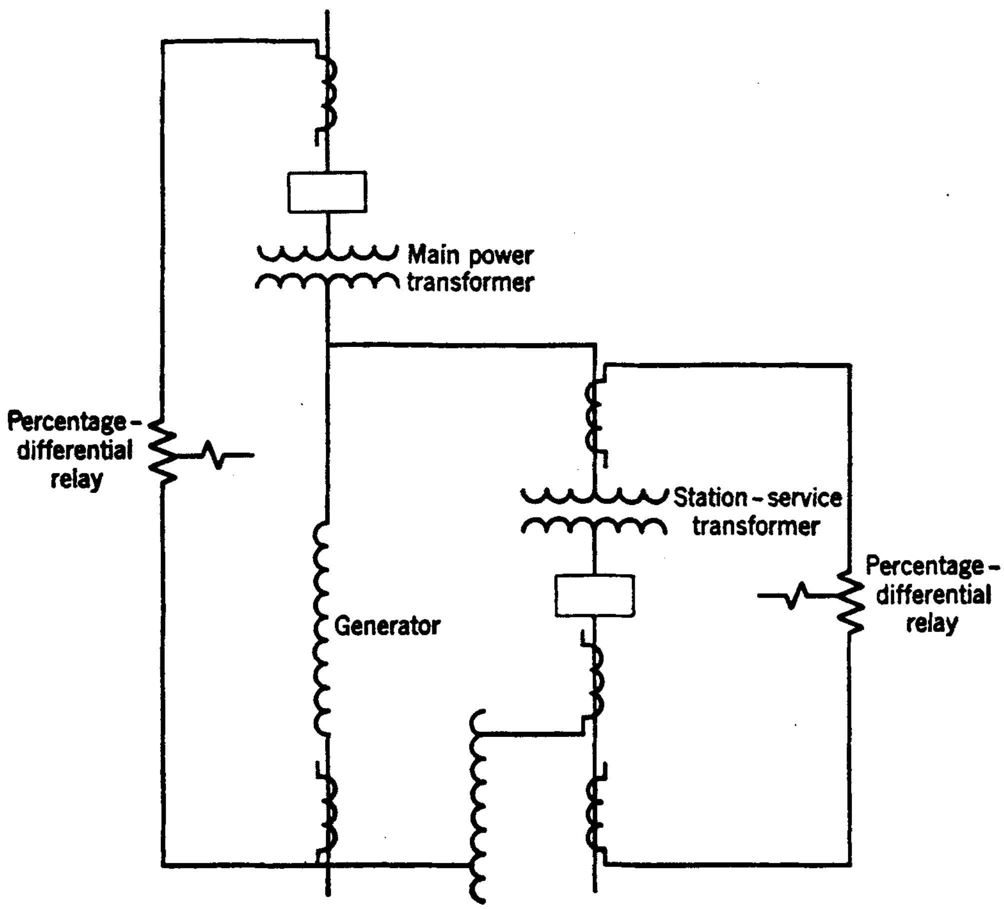


Fig. 4. Schematic connections for main and station-service-transformer protection.

around a circuit breaker, as explained in Chapter 1. A separate differential relay is used to protect the station-service power transformer because the relay protecting the main power transformer is not sensitive enough to provide this protection; with a steam-turbine generator, the station-service bank is no larger than about 10% of the size of the main bank, and, consequently, the CT's used for the main bank have ratios that are about 10 times as large as would be desired for the most sensitive protection of the station-service

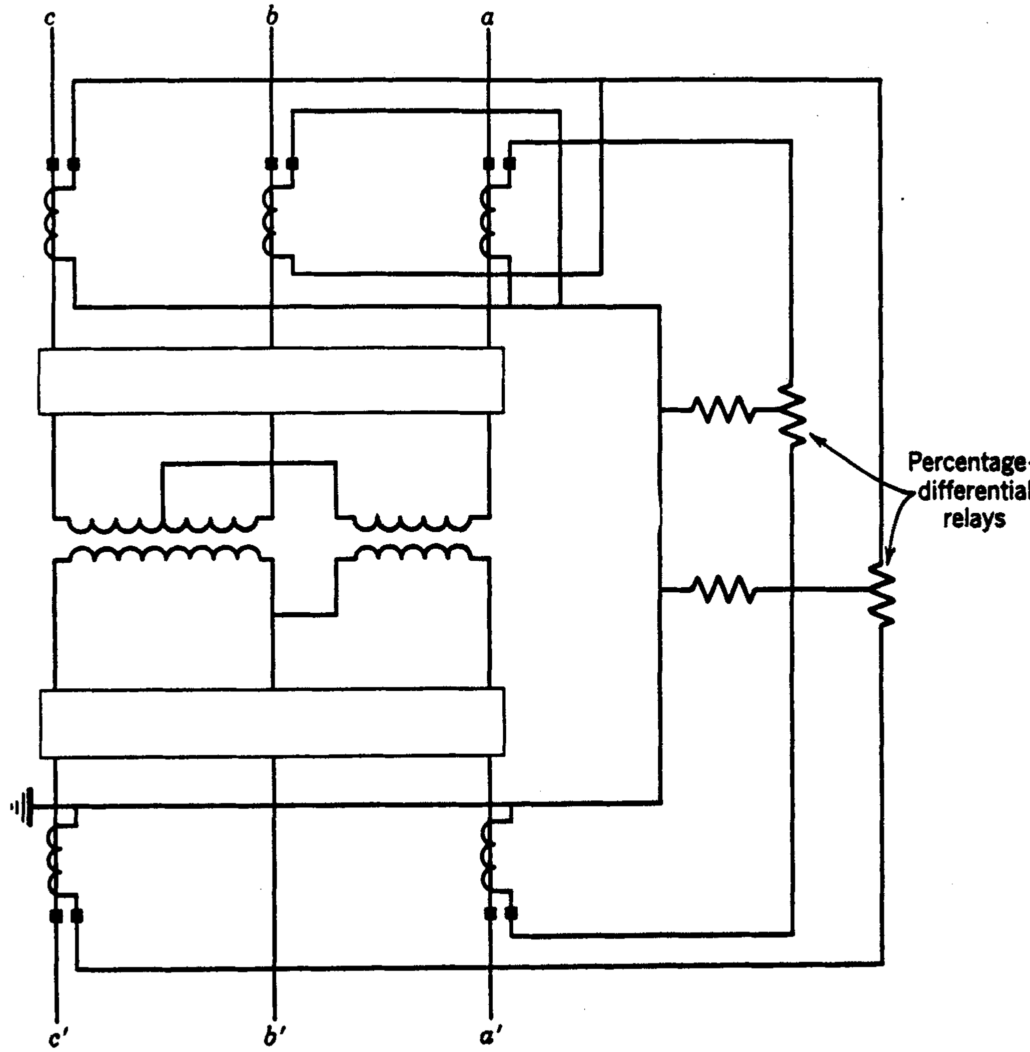


Fig. 5. Usual method of protecting a Scott-connected bank.

transformer. With a hydroelectric-turbine generator, the station-service transformer is more nearly 1% of the size of the main transformer; consequently, the impedance of the station-service transformer is so high that a fault on its low-voltage side cannot operate the relay protecting the main transformer even if the CT's are omitted from the low-voltage side of the station-service transformer; therefore, for hydroelectric generators it is the practice to omit these CT's and to retain separate differential protection for the station-service bank. In order to minimize the consequential damage should a station-service-transformer fault occur, separate high-speed percentage-differential relaying should be- used on the station-service transformer as for the main power transformer.

Figure 5 shows the usual way to protect a Scott-connected bank. This arrangement would not protect against a ground fault on phase b′, but, since this is on the low-voltage side where a ground-current source is unlikely, such a possibility is of little significance. A more

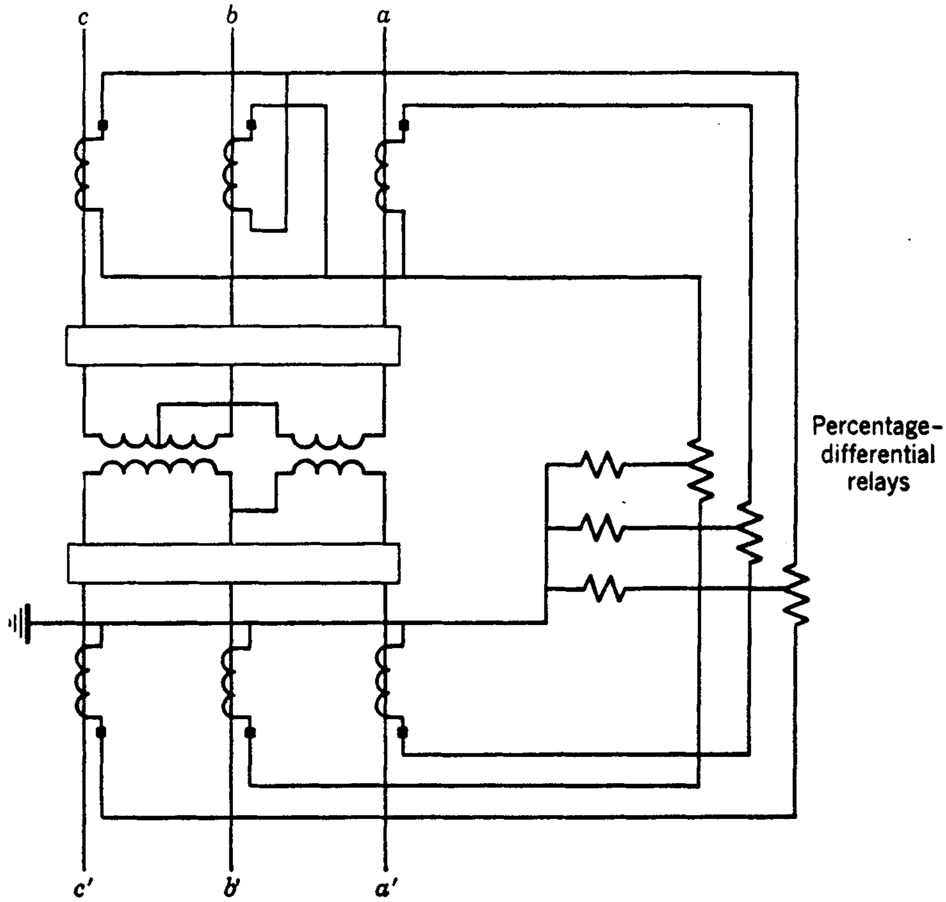


Fig. 6. Alternative protection of a Scott-connected bank.

practical objection to Fig. 5, but still of secondary significance, is that, for certain turn-to-turn or phase-to-phase faults, only one relay unit can operate. This is contrasted with the general practice of providing three relay units to protect three-phase banks where, for any phase-to-phase fault, two relay units can operate, thereby giving double assurance that at least one unit will cause tripping. However, since Scott-connected banks are used only at or near the load, it is questionable if the added cost of slightly more reliable protection can be justified. An alternative that does not have the technical disadvantages of Fig. 5 is shown in Fig. 6. Reference to other forms of Scott-connected bank and their differential protection is given in the Bibliography.[4]

Differentially connected CT's should be grounded at only one point. If more than one set of wye-connected CT's is involved, the neutrals should be interconnected with insulated wire and grounded at only one point. If grounds are made at two or more different points, even to a low-resistance ground bus, fault currents flowing in the ground or ground bus may produce large differences of potential between the CT grounds, and thereby cause current to flow in the differential circuit. Such a flow of current might cause undesired tripping by the differential relays or damage to the circuit conductors.

THE ZERO-PHASE-SEQUENCE-CURRENT SHUNT

The zero-phase-sequence-current shunt was described in Chapter 7. Such a shunt is useful where it is necessary to keep the zero-phase-sequence components of current out of the external secondary circuits of wye-connected CT's. Such a shunt would permit one to connect the CT's in wye on the wye side of a power transformer and in delta on the delta side. Advantage is seldom taken of this possibility because there is usually no hardship in

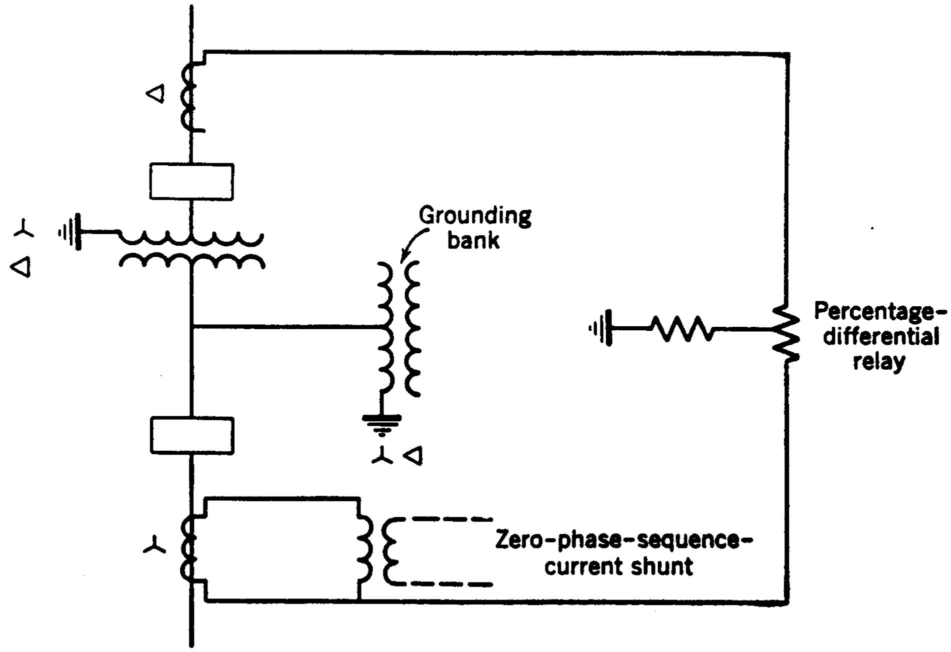


Fig. 7. Application of a zero-phase-sequence current shunt.

using the conventional connections, and in fact the conventional connections are usually preferred. The shunt is occasionally useful for the application of Fig. 7, where a grounding transformer on the delta side of a wye-delta power transformer is to be included within the zone of protection of the main bank. It is emphasized that, as indicated in Fig. 7, the neutral of the relay connection should not be connected to the neutral of the CT's or else the electiveness of the shunt will be decreased. Also, the CT's chosen for the shunt should not saturate for the voltages that can be impressed on them when large phase currents flow.

CURRENT-TRANSFORMER RATIOS FOR DIFFERENTIAL RELAYS

Most differential relays for power-transformer protection have taps, or are used with auxiliary autotransformers having taps, to compensate for the CT ratios not being exactly as desired. Where there is a choice of CT ratio, as with relaying-type bushing CT's, the best practice is to choose the highest CT ratio that will give a secondary current as nearly as possible equal to the lowest-rated relay tap. The purpose of this is to minimize the effect of the connecting circuit between the CT's and the relay (for the same reason that we use high voltage to minimize transmission-line losses). For whatever relay tap is used, the current supplied to the relay under maximum load conditions should be as nearly as possible equal to the continuous rating for that tap; this assures that the relay will be operating at its maximum sensitivity when faults occur. If the current supplied is only half the tap rating, the relay will be only half as sensitive, etc.

When choosing CT ratios for power transformers having more than two windings per phase, one should assume that each winding can carry the total rated phase load. The proper matching of the CT ratios and relay or autotransformer taps depends on the current-transformation ratios between the various power-transformer windings and not on their full-load-current ratings. This is because the relations between the currents that will flow in the windings during external faults will not depend on their rated-current values but on the current-transformation ratios.

CURRENT-TRANSFORMER ACCURACY REQUIREMENTS FOR DIFFERENTIAL RELAYS

It is generally necessary to make certain CT accuracy calculations when applying power-transformer differential relays. These calculations require a knowledge of the CT characteristics either in the form of ratio-correction-factor curves or secondary-excitation and impedance data.

Two types of calculations are generally required. First, it is necessary to know approximately what CT errors to expect for external faults. Percentage-differential relays for power-transformer protection generally have adjustable percent slopes. This subject will be treated in more detail later, but the knowledge of what the CT errors will be is one factor that determines the choice of the percent slope. The other type of calculation is to avoid the possibility of lockingin for internal faults, as was described in Chapter 10 for generator differential protection; such a calculation is particularly necessary with the "harmonic-current-restraint" relay, a type that will be described later. For detailed application procedures, the manufacturers' bulletins should be followed.

The example given in Chapter 10 of a method for calculating steady-state CT errors in a generator differential-relay circuit is also applicable to the power-transformer relay, with minor exceptions. The fact that some CT's may be in delta introduces a slight complication, but the circuit calculation is still simple.

A study based on certain equipment of the manufacturer with whom the author is associated showed the minimum requirements for bushing CT's to be as in the accompanying table. The fact that relaying-type bushing CT's may be operated on their lowest turns-ratio tap makes it necessary that the rating of the full winding be higher than if the full winding were used.

Number of Secondary Turns	ASA Accuracy Rating (Full Winding)
120	10L200
240	l0L400
400	l0L400
600	l0L400
800	10L800
1000	l0L800
1200	l0L800

CHOICE OF PERCENT SLOPE FOR DIFFERENTIAL RELAYS

Percentage-differential relays are generally available with different percent slopes; they may have adjustment so that a single relay can have any one of several slopes. The purpose of the percent-slope characteristic is to prevent undesired relay operation because of "unbalances" between CT's during external faults arising from an accumulation of unbalances for the following reasons: (1) tap-changing in the power transformer; (2) mismatch between CT currents and relay tap ratings; and (3) the difference between the errors of the CT's on either side of the power transformer. Many power transformers have taps that will give $\pm X\%$ change in transformation ratio. It is the practice to choose CT ratios and relay or autotransformer taps to balance the currents at the midpoint of the tap-changing range; on that basis, the most unbalance that can occur from this cause is $X\%$. The maximum unavoidable mismatch between CT currents and relay tap ratings is one-half of the difference between two relay tap ratings, expressed in percent. The percent difference between CT errors must be determined for the external fault that produces the greatest error; the best that we can do is to calculate this on a steady-state basis. We should assume that all three unbalances are in the same direction to get the total maximum possible unbalance. Then add at least 5% to this value, and the new total is the minimum percent slope that should be used.

PROTECTING A THREE-WINDING TRANSFORMER WITH A TWO-WINDING PERCENTAGE-DIFFERENTIAL RELAY

Unless there is a source of generation back of only one side of a power transformer, a two-winding percentage-differential relay should not be used to protect a three-winding transformer. Figure 8 shows that, when a two-winding relay is used, the CT secondaries on

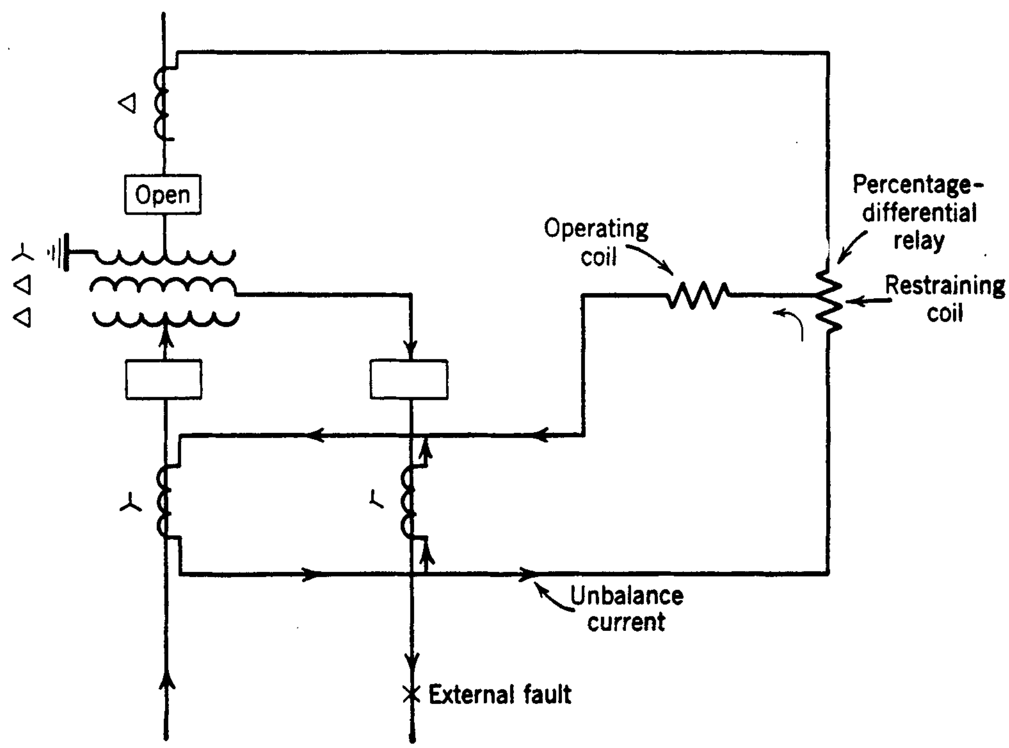


Fig. 8. A misapplication of a two-winding transformer differential relay.

two sides of the power transformer must be paralleled. If there is a source of generation back of one of these sides, the conditions shown by the arrows of Fig. 8 could exist. For an external fault on the other side there may be sufficient unbalance between the CT currents, either because of mismatch or errors or both, to cause the differential relay to operate undesirably. The relay would not have the benefit of through-current restraint, which is the basis for using the percentage-differential principle. Instead, only the unbalance current would flow in all of the operating coil and in half of the restraining coil; in effect, this constitutes a 200% unbalance, and it is only necessary that the unbalance current be above the relay's minimum pickup for the relay to operate.

Of course, if the two sides where CT's are paralleled in Fig. 8 supply load only and do not connect to a source of generation, a two-winding relay may be used with impunity.

Figure 9 shows that, if a three-winding relay is used, there will always be through-current restraint to restrain the relay against undesired operation.

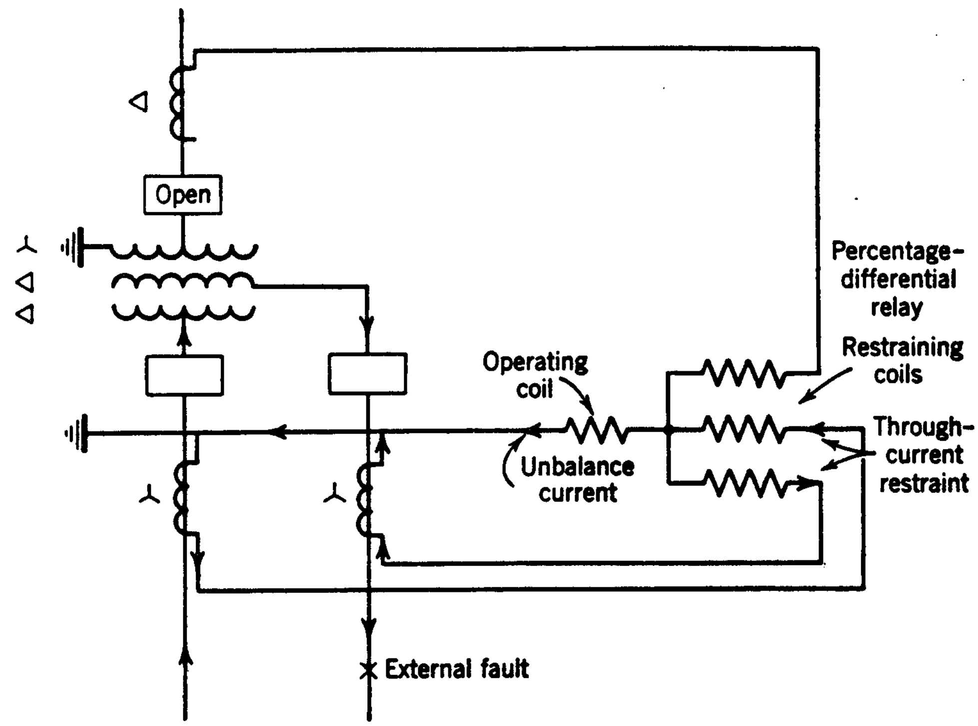


Fig. 9. Illustrating the advantage of a three-winding relay with a three-winding transformer.

A further advantage of a three-winding relay with a three-winding transformer is that, where relay types are involved having taps for matching the CT secondary currents, it is often unnecessary to use any auxiliary CT's. Thus, a three-winding relay may even be used with advantage where a two-winding relay might suffice. There is no disadvantage, other than a slight increase in cost, in using a three-winding relay on a two-winding transformer; no harm is done if one of the restraint circuits is left unconnected.

EFFECT OF MAGNETIZING-CURRENT INRUSH ON DIFFERENTIAL RELAYS

The way in which CT's are connected and the way in which CT ratios and relay taps are chosen for differential relaying neglect the power-transformer exciting-current component. Actually, this component causes current to flow in the relay's operating coil,

but it is so small under normal load conditions that the relay has no tendency to operate. However, any condition that calls for an instantaneous change in flux linkages in a power transformer will cause abnormally large magnetizing currents to flow, and these will produce an operating tendency in a differential relay.[5, 6, 7]

The largest inrush and the greatest relay-operating tendency occur when a transformer bank has been completely de-energized and then a circuit breaker is closed, thereby applying voltage to the windings on one side with the windings on the other side still disconnected from load or source. Reference 5 gives data as to the magnitudes and durations of such inrush currents. Considerably smaller but still possibly troublesome inrushes occur when a transformer with connected load is energized[7] or when a short circuit occurs or is disconnected.[8]

Another troublesome inrush problem will be discussed later under the heading "Protection of Parallel Transformer Banks."

The occasional tripping because of inrush when a transformer is energized is objectionable because it delays putting the transformer into service. One does not know but that the transformer may have a fault in it. Consequently, the safest thing to do is to make the necessary tests and inspection to locate the trouble, if any, and this takes considerable time.

Percentage-differential relays operating with time delay of about 0.2 second or more will often "ride over" the inrush period without operating. Where high-speed relays are required, it is generally necessary to use relay equipment that is especially designed to avoid undesired tripping on the inrush current.

Three methods that are used for preventing operation on inrush current will now be described.

Desensitizing. One type of desensitizing equipment consists of an undervoltage relay with *"b"* contacts and having time-delay pickup and reset; these contacts are connected in series with a low-resistance resistor that shunts the operating coil of the differential relay in each phase. This is shown schematically in Fig. 10 for the differential relay of one phase. The undervoltage relay is energized from a potential transformer connected to the power-transformer leads between the power transformer and its low-voltage breaker. When the power transformer is de-energized, the undervoltage relay resets, and its contacts complete the shunt circuit across the operating coil of the differential relay. The undervoltage relay will not pick up and open its contacts until a short time after the power transformer has been energized, thereby desensitizing the differential relay during the magnetizing-current-inrush period. During normal operation of the power transformer, the desensitizing circuit is open, thereby not interfering with the differential-relay sensitivity should a fault occur in the power transformer. Should a transformer fault occur that would reset the undervoltage relay, its time delay would prevent desensitizing the differential relay until after it had had more than sufficient time to operate if it was going to do so.

One disadvantage of such a desensitizing method is that it might delay tripping should a short circuit occur during the magnetizing-inrush period while the differential relay is desensitized. If the fault were severe enough to lower the voltage sufficiently so that the desensitizing relay could not pick up, tripping would depend on the current being high enough to operate the differential relay in its desensitized state. This is a rather serious

disadvantage in view of the fact that one of the most likely times for a fault to occur is when the bank is being energized. The other disadvantage is that this equipment cannot desensitize the differential relay against the possibility of undesired operation during the magnetizing inrush after the clearing of an external fault. This is not so serious a disadvantage because desensitizing of the type described here is used only with relays having about 0.2-second time delay, and there is practically no problem of tripping on voltage recovery with such relays.

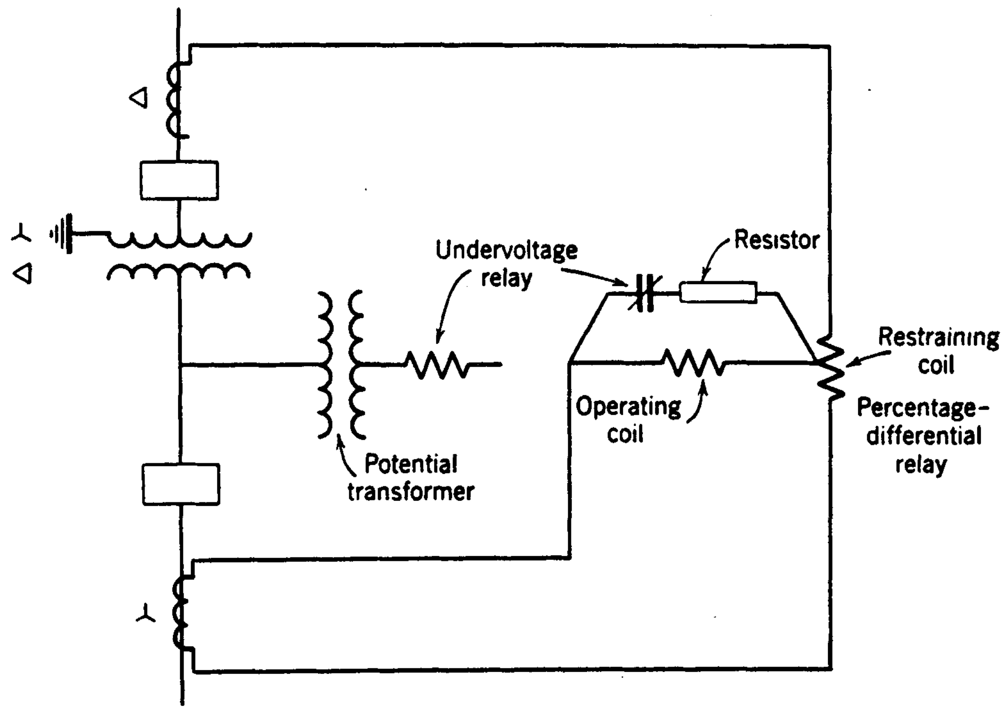


Fig. 10. Desensitizing equipment to prevent diferential-relay tripping on magnetizing inrush.

Tripping Suppressor.[9] An improvement over the desensitizing principle is called the "tripping suppressor." Three high-speed voltage relays, connected to be actuated by either phase-to-phase or phase-to voltage, control tripping by the percentage-differential relays. If all three voltage relays pick up during the inrush period, thereby indicating either a sound transformer or one with very low fault current, a timer is energized that closes its "*a*" contact in the tripping circuit of the differential relays after enough time delay so that tripping on inrush alone would not occur. But, for any fault that will operate a differential relay and also reduce the voltage enough so that at least one voltage relay will not pick up, tripping occurs immediately. In other words, tripping is delayed only for very-low-current faults that affect the voltage only slightly.

Any external fault that lowers the voltage enough to cause a significant inrush when the fault is cleared from the system will reset one or more of the voltage relays, thereby resetting the timer and opening the trip circuit long enough to assure that the differential relays will have reset if they had any tendency to operate.

The tripping suppressor is usable with either high-speed or slower differential relays, but its widest application is with high-speed relays. In fact, high-speed relays that are not inherently selective between inrush and fault currents require tripping suppressors.

Harmonic-Current Restraint.[10] The principle of "harmonic-current restraint" makes a differential relay self-desensitizing during the magnetizing-current-inrush period, but the relay is not desensitized if a short circuit should occur in the transformer during the magnetizing-inrush period. This relay is able to distinguish the difference between magnetizing-inrush current and short-circuit current by the difference in wave shape. Magnetizing-inrush current is characterized by large harmonic components that are not noticeably present in short-circuit current. A harmonic analysis of a typical magnetizing-inrush-current wave was as shown in the accompanying table.

Harmonic Component	Amplitude in Percent of Fundamental
2nd	63.0
3rd	26.8
4th	5.1
5th	4.1
6th	3.7
7th	2.4

Figure 11 shows how the relay is arranged to take advantage of the harmonic content of the current wave to be selective between faults and magnetizing inrush.

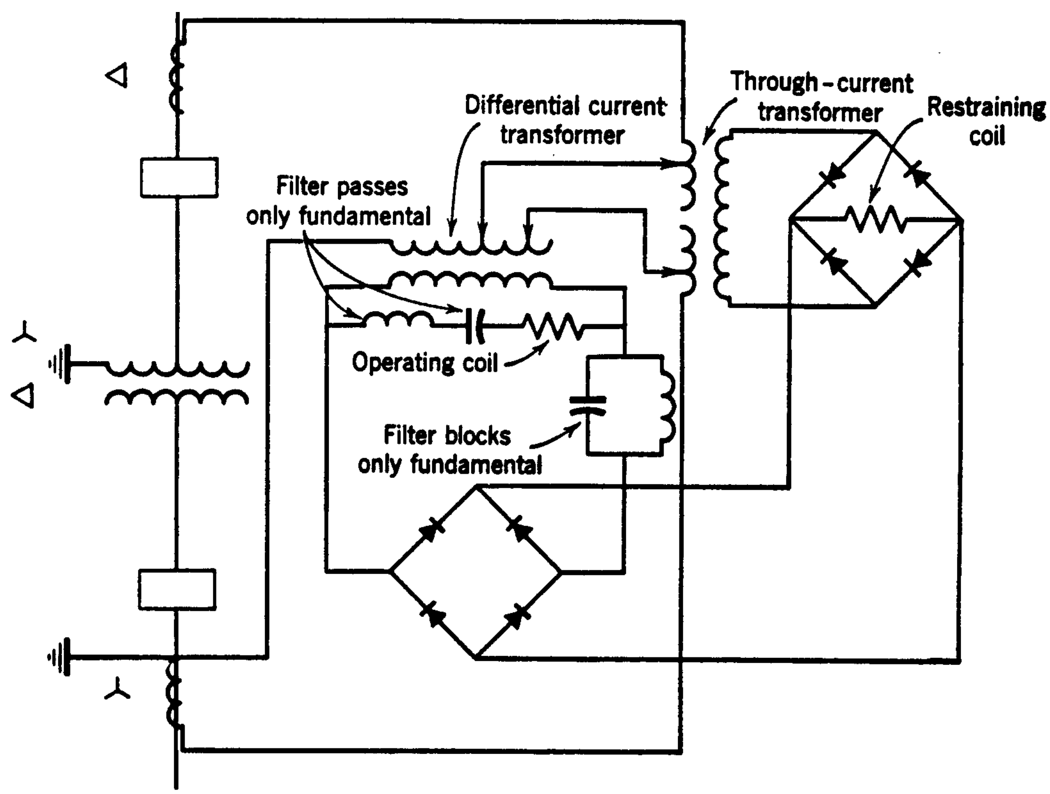


Fig. 11. Harmonic-current-restraint percentage-differential relay.

Figure 11 shows that the restraining coil will receive from the through-current transformer the rectified sum of the fundamental and harmonic components. The operating coil will receive from the differential-current transformer only the fundamental component of the differential current, the harmonics being separated, rectified, and fed back into the restraining coil.

The direct-current component, present in both magnetizing-inrush and offset fault current, is largely blocked by the differential-current and the through-current transformers, and produces only a slight momentary restraining effect.

PROTECTION OF PARALLEL TRANSFORMER BANKS

From the standpoint of protective relaying, the operation of two transformer banks in parallel without individual breakers is to be avoided. In order to obtain protection equivalent to that when individual breakers are used, the connections of Fig. 12 would be required. To protect two equally rated banks as a unit, using only CT's on the source sides of the common breakers and a single relay is only half as sensitive as protecting each bank from its own CT's; this is because the CT ratios must be twice as high as if individual CT's were used for each bank, both banks being assumed to have the same rating, and as a result the secondary current for a given fault will be only half as high. If one bank is smaller than the other, its protection will be less than half as sensitive. With more than two banks, the protection is still poorer.

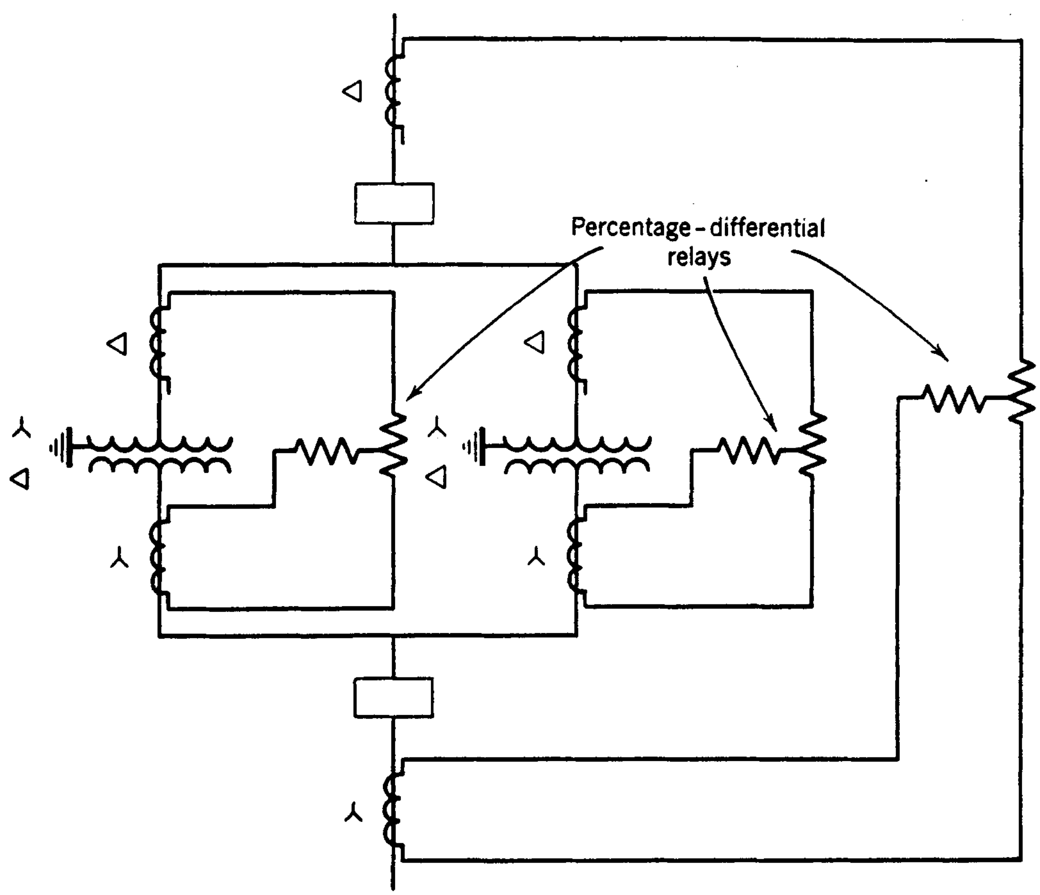


Fig. 12. The protection of parallel transformer banks with common breakers.

When parallel transformer banks having individual breakers are located some distance away from any generating station, a possibly troublesome magnetizing-current-inrush problem may arise.[11] If one bank is already energized and a second bank is then energized, magnetizing-current inrush will occur—not only to the bank being energized but also to the bank that is already energized. Moreover, the inrush current to both banks will decay at a much slower rate than when a single bank is energized with no other banks in parallel. The magnitude of the inrush to the bank already connected will not be as high as that to the bank being switched, but it can easily exceed twice the full-load-current rating of the bank; the presence of load on the bank will slightly reduce its inrush and increase its rate of decay.

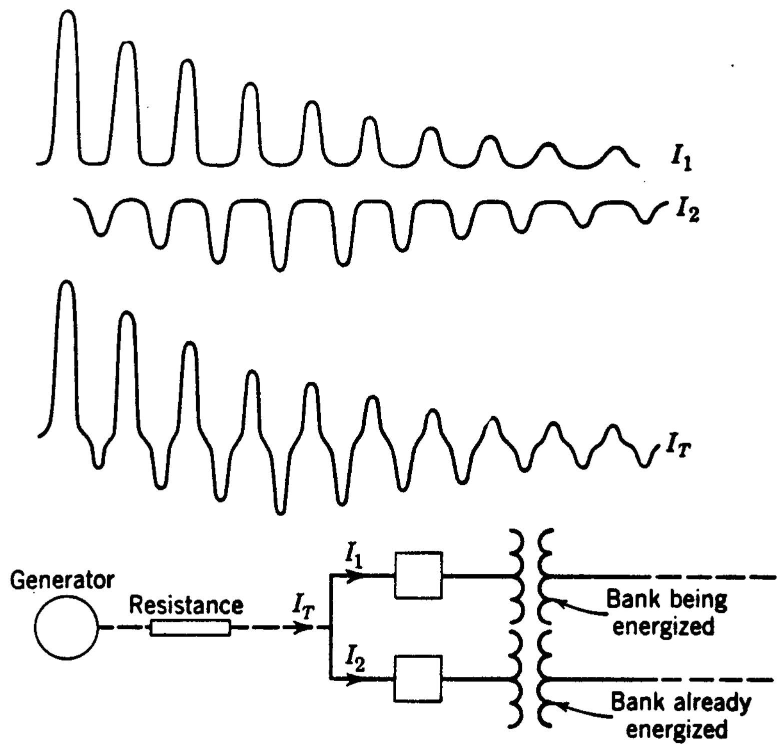


Fig. 13. Prolonged inrush currents with parallel transformers.

Briefly, the cause of the foregoing is as follows: The d-c component of the inrush current to the bank being energized flows through the resistance of transmission-line circuits between the transformer banks and the source of generation, thereby producing a d-c voltage-drop component in the voltage applied to the banks. This d-c component of voltage causes a build-up of d-c magnetizing current in the already-connected bank, the rate of which is the same as the rate at which the d-c component of magnetizing current is decreasing in the bank just energized. When the magnitudes of the d-c components in both banks become equal, there is no d–c component in the transmission-line circuit feeding the banks, but there is a d-c component circulating in the loop circuit between the banks. The time constant of this trapped d–c circulating current, depending only on the constants of the loop circuit, is much longer than the time constant of the d-c component in the transmission-line circuit feeding the banks. Figure 13 shows the circuits involved and the magnetizing-current components in each circuit.

The significance of the foregoing is two-fold. First, desensitizing means already described for preventing differential-relay operation on magnetizing-current inrush are not effective

in the bank that is already energized. Only time delay in the operation of the differential relay will be elective in preventing undesired tripping. However, if the banks are protected by separate relays having tripping suppression or harmonic restraint, no undesired tripping will occur. Second, if the banks are protected as a unit, even the harmonic-current restraint type may cause undesired tripping because, as shown in Fig. 13, the total-current wave very shortly becomes symmetrical and does not contain the necessary even harmonics required for restraint.

SHORT-CIRCUIT PROTECTION WITH OVERCURRENT RELAYS

Overcurrent relaying is used for fault protection of transformers having circuit breakers only when the cost of differential relaying cannot be justified. Overcurrent relaying cannot begin to compare with differential relaying in sensitivity.

Three CT's, one in each phase, and at least two overcurrent phase relays and one overcurrent ground relay should be provided on each side of the transformer bank that is connected through a circuit breaker to a source of short-circuit current. The overcurrent relays should have an inverse-time element whose pickup can be adjusted to somewhat above maximum rated load current, say about 150% of maximum, and with sufficient time delay so as to be selective with the relaying equipment of adjacent system elements during external faults. The relays should also have an instantaneous element whose pickup can be made slightly higher than either the maximum short-circuit current for an external fault or the magnetizing-current inrush.

When the transformer bank is connected to more than one source of short-circuit current, it may be necessary for at least some of the overcurrent relays to be directional in order to obtain good protection as well as selectivity for external faults.

The overcurrent relays for short-circuit protection of transformers provide also the external-fault back-up protection discussed elsewhere.

GAS-ACCUMULATOR AND PRESSURE RELAYS

A combination gas-accumulator and pressure relay, called the "Buchholz" relay after its inventor, has been in successful service for over 30 years in Europe and for 10 years in Canada.[12] This relay is applicable only to a so-called "conservator-type" transformer in which the transformer tank is completely filled with oil, and a pipe connects the transformer tank to an auxiliary tank, or "conservator," which acts as an expansion chamber. In the piping between the main tank and the conservator are the two elements of the relay. One element is a gas-collecting chamber in which gas evolved from the slow breakdown of insulation in the presence of a small electric arc is collected; when a certain amount of gas has been collected a contact closes, usually to sound an alarm. The collected gas may be drawn into a gas analyzer to determine what kind of insulation is being broken down and thereby to learn whether lamination, core-bolt, or major insulation is being deteriorated. This gas analyzer is not a part of the Buchholz relay. The other element contains a vane that is operated by the rush of oil through the piping when a severe fault occurs, to close contacts that trip the transformer breakers.

The gas-accumulator element of the Buchholz type of relay has not had extensive use in the United States, partly because the value of such protection "has been underestimated,"[2] and partly because conservator-type transformers are not being built here in any quantity. From Canada, where such relays are widely used, come very favorable reports of the protection that they provide on conservator-type transformers.[13, 15]

However, pressure relays, applicable to gas-cushioned transformers, are being used to an increasing extent in the United States. A relay operating in response to rate-of-rise of pressure has been introduced that uses the pressure in the gas cushion.[14] Such relays are valuable supplements to differential or other forms of relaying, particularly for transformers with complicated circuits that are not well suited to differential relaying, such as certain regulating and rectifier transformers; they will be considered later.

Many of those familiar with the Buchholz relay feel that the gas-accumulator element is more valuable than the pressure element. The gas-accumulator element gives early warning of incipient faults, permitting the transformer to be taken out of service and repaired before extensive damage is done. How valuable this feature is depends on how large a proportion of the total number of faults is of the incipient type, such as failures of core-bolt or lamination insulation, and high-resistance or defective joints in windings. Also, the gas-accumulator feature is valuable only if there is also in service a thoroughly reliable protective equipment that will quickly disconnect the transformer when a short circuit occurs.

From the foregoing it will be evident that gas-accumulator and pressure relays are valuable principally as supplements to other forms of protection. In the first place, a transformer must be of the type that lends itself to this type of protection. Then, protection is provided only for faults inside the transformer tank; differential or other types of relaying must be provided for protection in the event of external bushing fiashovers or faults in the connections between a transformer and its circuit breakers. Where sensitive and reliable gas-accumulator and pressure relays are applicable, the other relaying equipment need not be nearly as sensitive, and therefore the problem of preventing undesired operation on magnetizing-current inrush is greatly simplified. In fact, it has been suggested that, where gas and pressure relaying is used, it is good practice to "try again" if a differential or other relay operates when a transformer bank is energized, so long as the gas or pressure elements do not indicate any internal fault.[15]

GROUNDING PROTECTIVE RELAY

On grounded-neutral systems, protection can be provided by insulating a transformer tank from ground except for a connection to ground through a CT whose secondary energizes an overcurrent relay. Such an arrangement will give sensitive protection for arc-overs to the tank or to the core, but it will not respond to turn faults or to faults in the leads to the transformer.

REMOTE TRIPPING

When a transmission line terminates in a single transformer bank, the practice is frequently to omit the high-voltage breaker and thereby avoid considerable expense. Such practice is made possible by what is called "transferred tripping" or, preferably, "remote tripping."[16]

Remote tripping is the tripping of the circuit breaker at the other end of the transmission line for faults in the power transformer. The protective relays at that other end of the line are not sensitive enough to detect turn faults inside the transformer bank. Consequently, the transformer bank's own differential-relaying equipment trips the bank's low-voltage breaker and initiates tripping of the breaker at the other end of the line in one of two basic ways.

One way to cause the distant relays to operate and trip their breaker is to throw a short circuit on the line at the high-voltage terminals of the power transformer.[16,17] This is done by arranging the transformer-differential relays to trip the latch of a spring-closed air-break-type disconnecting switch that grounds one or three phases of the line. A three-phase switch is used if there is automatic reclosing at the other end of the line; this is to protect the transformer against further damage by preventing the reapplication of voltage to the transformer. If automatic reclosing is not used, and if the station is attended, a single-phase switch is sufficient.

The principal disadvantage of the grounding-disconnect method of remote tripping is that it is relatively slow. To the closing time of the switch must be added the operating time of the relaying equipment at the other end and the tripping time of the breaker there; this total time may amount to about a half second or more, which is long for transformer protection. Of course, if a three-phase grounding switch is used, the transformer is de-energized as soon as the switch closes. Another disadvantage is that, where automatic reclosing is used, the system is subjected to the shock of one or more reclosings on a short circuit. It may be necessary to delay reclosing to be sure that the grounding switch is closed first when high-voltage transformer-bushing flashovers occur. That these disadvantages are not always too serious is shown by the fact that about half of the installations in this country use this method.

The other way to trip the distant breaker is with a pilot.[16,18] Any of the types of pilot (wire, carrier-current, or microwave) may be used, depending on the circumstances. In any event, the equipment must be free of the possibility of undesired tripping because of extraneous causes; this is achieved by transmitting a tripping signal that is not apt to be duplicated otherwise. One of the most successful methods is the so-called "frequency-shift" system;[18] not only is this system most reliable but it is also high speed, requiring only about 3 cycles to energize the trip coil of the distant breaker after the transformer-differential relay has closed its tripping contacts. By using two frequency-shift channels, the equipment can be tested without removing it from service.

An inherent advantage of remote tripping over a pilot is that the received tripping signal can also block automatic reclosing. It may be necessary, however, to delay reclosing a few cycles to be sure that reclosing is blocked when high-voltage transformer-bushing flashovers occur.

A differentially protected transformer bank should have inverse relays, preferably energized from CT's other than those associated with the differential relays, to trip fault-side breakers when external faults persist for too long a time. An exception is the transformer bank of a unit generator-transformer arrangement where the generator's external-fault back-up relays provide all the necessary back-up protection. The back-up relays should preferably be operated from CT's located as in Fig. 14; this makes it unnecessary to adjust the relays so as not to operate on magnetizing-current inrush and hence permits greater sensitivity and speed if desired. When the transformer is connected to more than one source of short-circuit current, backup relays in all the circuits are required, and at least some may need to be directional, as indicated in Fig. 15, for good protection and selectivity. Each set of back-up relays should trip only its associated breaker, also as indicated in Fig. 15.

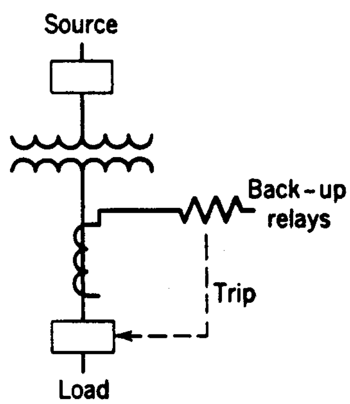


Fig. 14. Back-up relaying for transformer connected to one source.

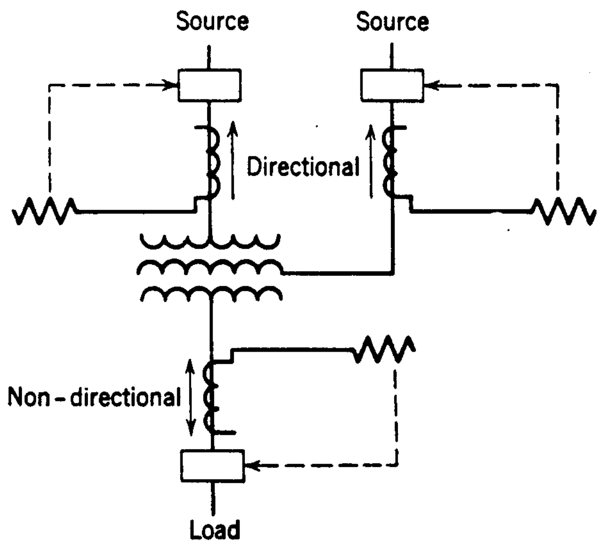


Fig. 15. Back-up relaying with two sources.

When a transformer has overcurrent relaying for short-circuit protection because the cost of differential relaying cannot be justified, the same overcurrent relays are used for back-up protection. It is realized that combining the two functions may work to the disadvantage of one or both, but this is the price that one must pay to minimize the investment.

REGULATING TRANSFORMERS

Regulating transformers may be of the "in-phase" type or the "phase-shifting" type. The in-phase type provides means for increasing or decreasing the circuit voltage at its location under load without changing the phase angle. The phase-shifting type changes the phase angle–and usually also the voltage magnitude–under load.

A regulating transformer may be used alone in a circuit or in conjunction with a power transformer. Or the regulating-transformer function may be built into a power transformer.

Figure 16 shows schematically the relay equipment that is recommended for protection against internal short circuits. Percentage-differential relaying, like that for generators, should be used to protect the series winding and its connections to its breakers. If the regulating transformer is close enough to a power transformer in the same circuit, the differential-protection zone of the power transformer may be extended to include the regulating transformer. The percent slope of the differential relay should be high enough to accommodate the full range of voltage change, as already mentioned for tap-changing power transformers.

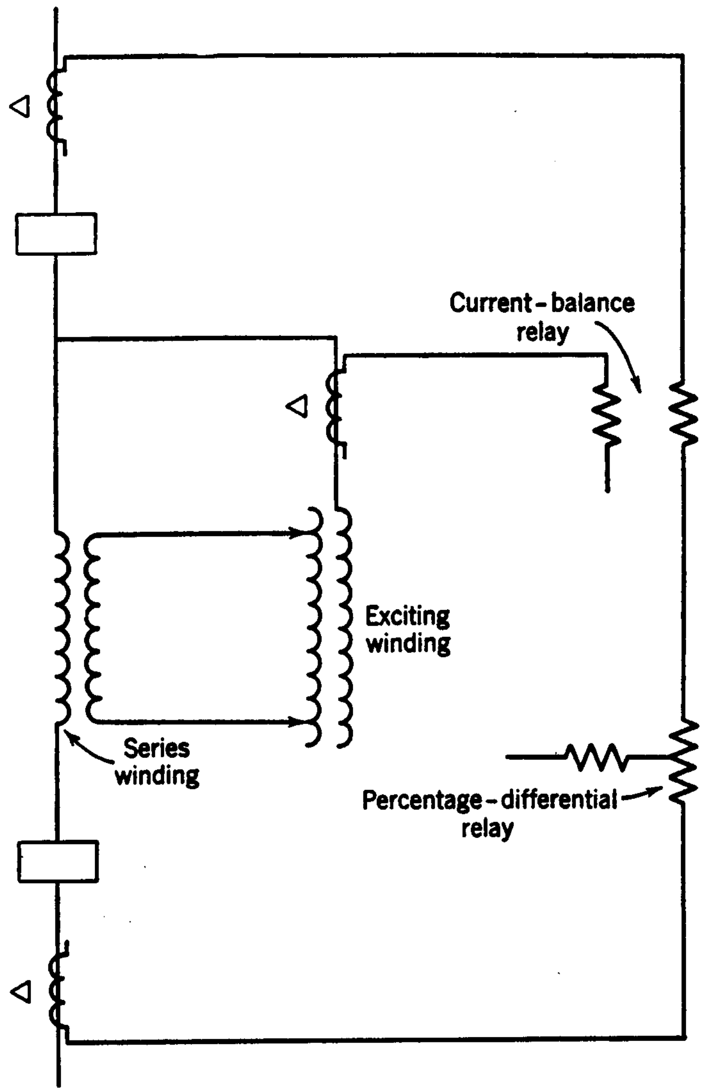
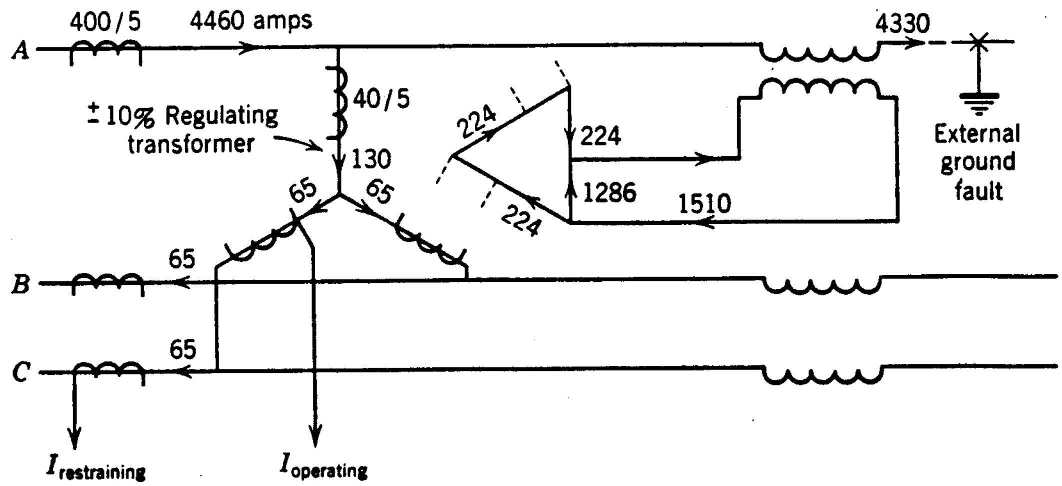


Fig. 16. Protection of an in-phase regulating transformer.

The exciting windings need separate protective equipment because the equipment protecting the series winding is not sensitive enough for the exciting windings. This is because the full-load-current rating of the exciting winding is much less than that of the series winding and the short-circuit current is proportionally less; for example, in a regulating transformer that changes the circuit voltage by ±10%, the full-load-current rating of the exciting winding will be 10% of that of the series winding. The situation is

the same as that already described for protecting two different-sized power transformers with one differential relay. In practice a current-balance relay protects the exciting winding, as shown in Fig. 16. So long as there is no fault in the exciting windings, the exciting current of a ±10% transformer will never exceed 10% of the rated series-winding current; the current-balance relay will operate whenever the ratio of exciting-winding current to series-winding current is about 25% higher than the maximum normal ratio under conditions of maximum buck or boost.



With Y CT's				With Δ CT's		
Phase	I_{op}	I_{restr}		Phase	I_{op}	I_{restr}
A	16.3	55.8		*A-B*	24.4	56.6
B	8.1	0.8		*B-C*	0	0
C	8.1	0.8		*C-A*	24.4	56.6

Fig. 17. Illustrating why delta-connected CT's are required for regulating-transformer protection.

A very important precaution is that the CT's supplying the current-balance relay must always be delta connected. This is so whether the neutral of the exciting windings is grounded or not. Figure 17 shows the results of a study of an actual application where an external phase-to-ground fault would cause the current-balance relays of phases *B* and *C* to operate incorrectly if the CT's were wye connected.

Wherever possible, it is recommended that gas-accumulator and pressure relaying supplement the other protective equipment. Or, if the regulating-transformer tank can be insulated from ground, a grounding protective relay would be recommended because of the more sensitive protection that it would provide.

PROTECTION OF PHASE-SHIFTING TYPE

Wherever possible, the phase-shifting type of regulating transformer is protected in the same manner as the in-phase type. However, with conventional percentage-differential relaying, a 10° phase shift is about all that can be tolerated; such a phase shift requires that

the differential relays have about a 40% slope and that relays in two phases operate before tripping is permitted, in order not to trip undesirably for external faults.

When phase shifts of more than about 10° are involved, special forms of relaying equipment are necessary. Certain modifications to conventional differential relaying may sometimes be possible, but the basis for such modifications is too complicated to consider here. Gas-accumulator and pressure relaying take on more importance where over-all differential relaying is not completely adequate. Complete percentage-differential protection can often be provided for wye windings if CT's are made available at both ends of each winding,[19] or differential protection against ground faults only can be provided if CT's at the neutral ends are lacking. Overcurrent relaying can protect against ground faults in a delta winding connected to a grounded-neutral source.

EXTERNAL-FAULT BACK-UP PROTECTION

The external-fault back-up relays of the power transformer or circuit associated with the regulating transformer will provide the necessary backup protection.

STEP VOLTAGE REGULATORS

If circuit breakers are provided, pressure relaying should be used for regulators whose equivalent physical size is about 1000 kva or more.

GROUNDING TRANSFORMERS

Two types of grounding transformer are in general use: (1) the wye-delta transformer, and (2) the zig-zag transformer. The neutral of either type may be grounded directly or through current-limiting impedance. It is assumed here that neither load nor a source of generation is connected to the delta winding of the wye-delta transformer and that the zig-zag transformer does not have another winding connected to load or generation; should either type have such connections, it would be treated as an ordinary power transformer.

Figure 18 shows the recommended way to protect either type of bank. For external ground faults, only zero-phase-sequence currents flow through the primaries of the delta-connected CT's. Therefore, current will flow only in the external-fault back-up overcurrent relay, and its time delay should be long enough to be selective with other relays that should operate for external faults. The other three relays will provide protection for short circuits on the grounding-transformer side of the CT's. These relays may be sensitive and quite fast because, except for magnetizing current and small currents that may flow through the relays because of CT errors, current will flow only when short circuits requiring tripping occur. The pickup of the overcurrent relays should be 25% to 50% of the grounding-transformer's continuous-current rating, and the primary-current rating of the CT's should be about the continuous-current rating of the power transformer.

An interesting fact in connection with either type of grounding bank is that, under certain conditions, it is impossible to have certain types of fault in the bank without the short-circuit current's being limited by some magnetizing impedance. For example, certain types of fault can occur without the limiting effect of magnetizing impedance only if there is another grounding bank to provide a zero-phase-sequence-circulating-current path for the

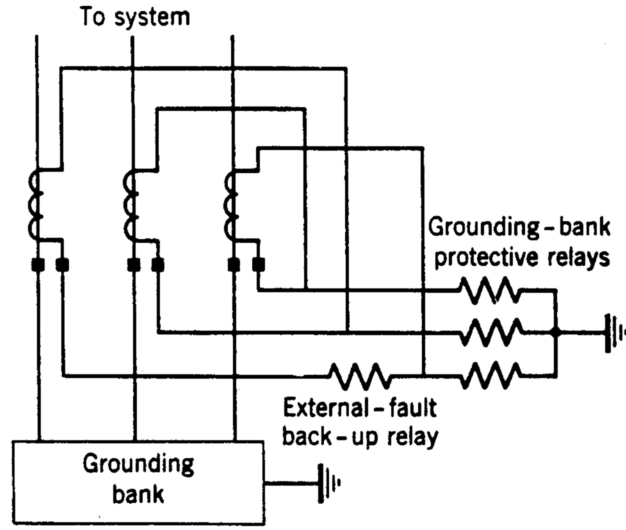


Fig. 18. Grounding-bank protection.

currents in the faulted bank; this other grounding bank may or may not have a delta winding connected to a source of generation. Or the fault must occur between certain points of the windings, and the presence of another grounding bank may or may not be necessary. Examples of the foregoing facts are shown in Figs. 19(*a*), 19(*b*), and 19(*c*) for a zig-zag bank. Remember that, unless fault current can flow in windings on the same core in such a way that the ampere-turns cancel, the current will be limited by some magnetizing impedance. However, if enough of a winding is shorted out, considerable overvoltage impressed on the remaining portion would cause large magnetizing currents to flow because of saturation. Figure 19(*a*) is an example of a type of short circuit where

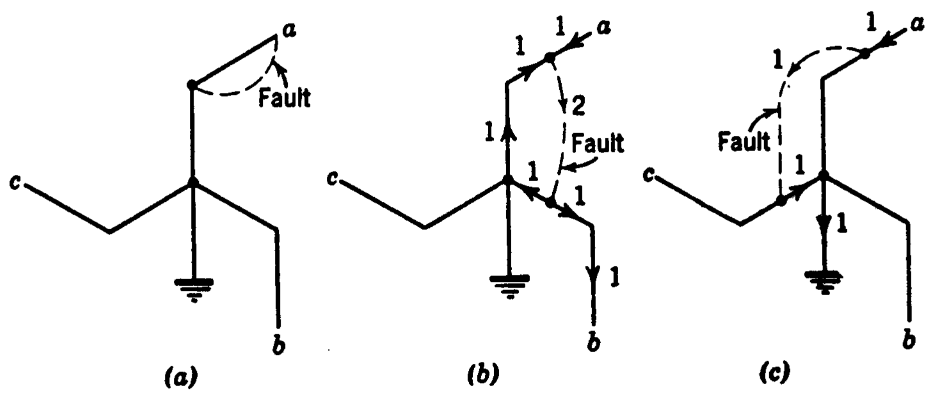


Fig. 19. Examples of faults in zig-zag banks. High-voltage side.

the current is limited by some magnetizing impedance of a winding. Figure 19(*b*) shows a type of short circuit that can occur without requiring the presence of another grounding bank; here, the fault is assumed to occur between the middle points of the two windings involved, and the relative magnitudes and directions of the currents are shown. Figure 19(*c*) shows a type of fault that requires the presence of a grounding bank with or without a delta connected to a source of generation; here again, the fault is between the middle points of the two windings involved. A good exercise for the reader is to trace the flow of current back through the other grounding bank, and also to apply other types of short circuit, to see if there is any way in which current can flow to cancel the ampere-turns on

each core involved. Figures 19(*a*), 19(*b*), and 19(*c*) are not the only examples of the three different conditions.

Because faults can occur that will not cause high currents to flow, gas-accumulator relaying, if applicable, would provide valuable supplementary protection.

ELECTRIC ARC-FURNACE TRANSFORMERS

Electric arc-furnace power transformers are not protected with percentage-differential relays because of the complications that would be introduced by the very frequent tap changing on the power transformer. Every time a furnace-transformer tap was changed, the low-voltage CT ratio or a tap on the relay would have to be changed.

Also, the connections of the furnace-transformer primary windings are usually changed from delta to wye and back again, which would require changing the CT connections.

Protection against short circuits inside the power transformer should be provided by inverse-time phase (and ground if required) overcurrent relays operating from the current on the high-voltage side of the power transformer. The phase relays should have torque-control coils and should be adjusted to pick up at currents only slightly in excess of the transformer's rated full-load current; they should have time delay only long enough to prevent operation on transformer magnetizing-current inrush. High-speed overcurrent relays on the low-voltage side of the transformer, adjusted to pick up at current slightly above rated full load but slightly below the current that will pick up the high-voltage phase relays, should be arranged to control the operation of the high-voltage phase relays through their torque-control coils so as to permit the high-voltage relays to operate only when the low-voltage relays do not operate. In this way, the high-voltage relays may normally be sensitive and fast so as to provide as good protection to the transformer as it is possible to provide with overcurrent relays, while at the same time avoiding undesired operation on external faults, the most common of which are short circuits in the furnace.

For primary protection against short circuits between the "back-up" breaker and the power transformer, and for back-up protection against faults in the transformer or beyond it, inverse-time phase (and ground if required) overcurrent relays should be provided. These relays should obtain their current from the source side of the back-up breaker. This so-called "back-up" breaker is the breaker that is provided to interrupt short-circuit currents in the transformer or on the high-voltage side, and it may serve several transformers.

Both of the foregoing groups of relays should trip the back-up breaker.

POWER-RECTIFIER TRANSFORMERS

Inverse-time-overcurrent relays are recommended for internal short-circuit protection. The inverse-time elements should have time-delay adjustment with just sufficient delay to be selective with the d-c protective equipment for external d-c short circuits or overloads. The instantaneous elements should be adjustable so as barely not to operate for low-voltage faults or magnetizing-current inrush, including an allowance for over travel.

A temperature relay operating in conjunction with a resistance-temperature detector should be provided to sound an alarm or trip the transformer breaker as desired.

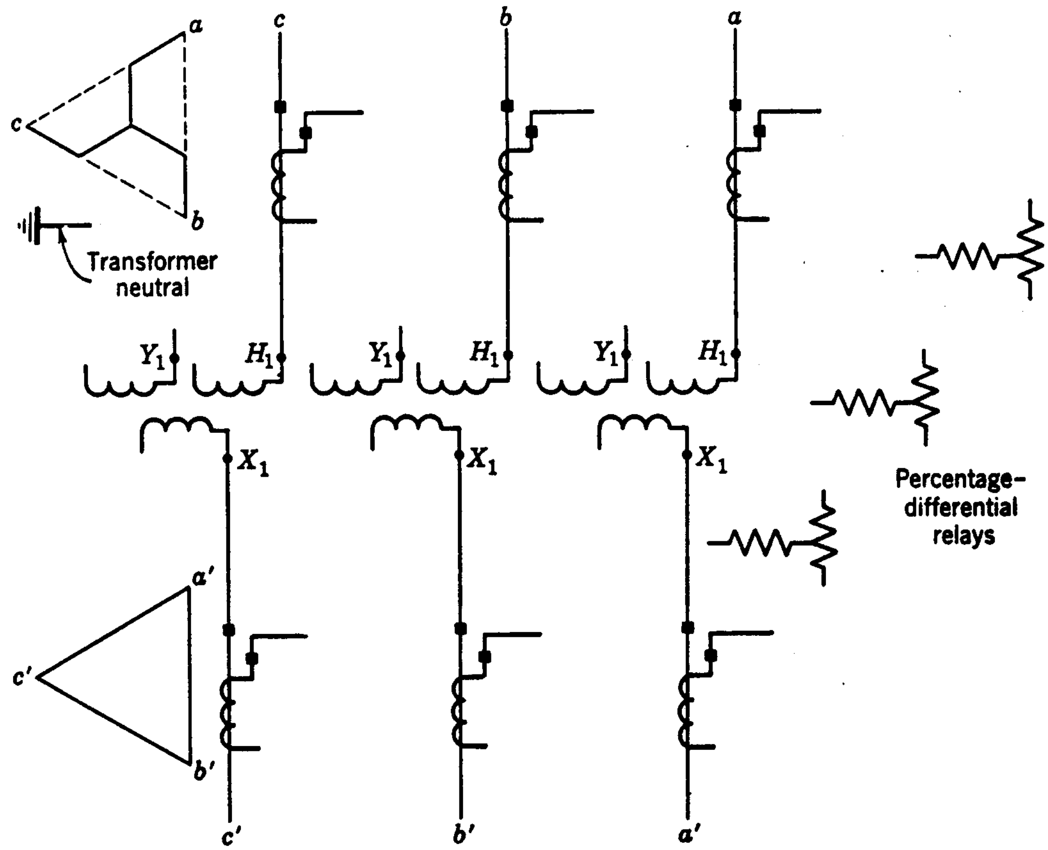


Fig. 20. Illustration for Problem 1.

PROBLEMS

1. Given three single-phase power transformers having windings as shown in Fig. 20. Complete the connections of the power transformers so as to obtain a zig-zag connection on the high voltage side and a delta connection on the low-voltage side, using the partial connections shown, the voltage diagrams to be as shown. Connect the CT's to the percentage-differential relays so as to obtain protection of the transformer bank for internal faults but so that undesired tripping will not occur for external faults. Assume a 1/1 turn ratio between each pair of power-transformer windings, and assume that any desired ratio is available for the CT's. Add the CT-secondary ground connection.

2. Given a wye-delta power transformer protected as shown in Fig. 21. An external three-phase fault occurs, and fault currents flow through the transformer with the magnitudes as shown. Will the differential relay operate to trip ?

3. Repeat Problem 2 except with a three-phase fault between the high-voltage breaker and the transformer. Assume that the system supplies 4000 amperes three-phase to the fault, the current supplied by the power transformer being the same as in Problem 2.

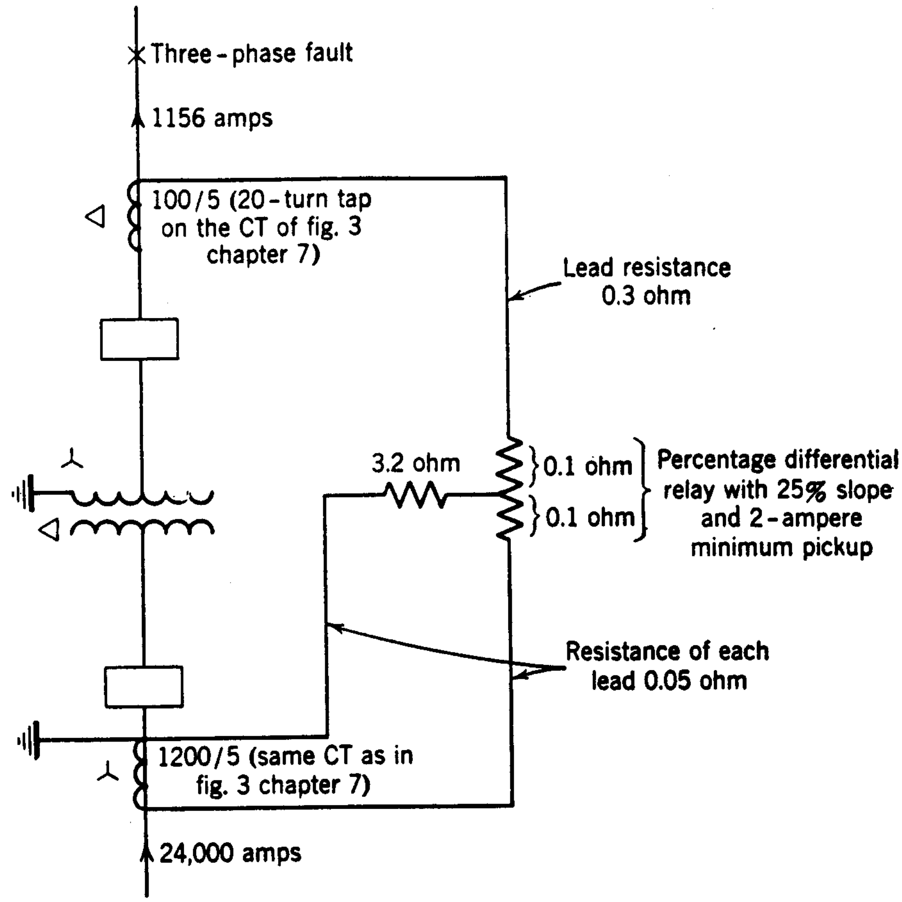


Fig. 21. Illustration for Problems 2 and 3.

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